An Analytical Calibration Approach for Microwave Polarimetric Radiometers

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***Abstract*—We present an analytical calibration approach for passive microwave polarimeters that is applicable where the instrument can be partitioned into distinct, functional radio-frequency blocks. The methodology is focused on polarimetric system characterization, not polarimetric measurements. It requires characterization of each major internal functional subsystem with a vector network analyzer to obtain a closed-form transfer function. The goals of this approach are to provide a transfer function describing the system in its entirety and to isolate the contribution of each subsystem to the uncertainty in the final modified Stokes parameters. Notably, the approach does not assume ideal polarization isolation in the radiometer system. A significant benefit of this approach is that the cascaded transfer functions serve as a realistic instrument simulator revealing where improvements in component performance would have greatest benefit for system performance over the dynamic range of the instrument. This systems-focused approach is applied to the National Aeronautics and Space Admnistration Goddard Space Flight Center polarimetric Airborne C-band Microwave Radiometer (ACMR), whose architecture allows the necessary subsystem partitioning. The characteristics of each subsystem were extensively measured, converted to a transfer function, and imported into the overall closed-form system model. Inversion of the system model and error analysis inherent to this calibration approach are illustrated by a full Stokes parameter retrieval for a senescent cornfield.**

***Index Terms*—Calibration, error analysis, microwave radiometry, polarimetry, remote sensing, soil measurements.**

I. Introduction

THERMAL microwave spectral radiance is fully described by the four-component modified Stokes vector. Under the Rayleigh–Jeans approximation, this vector can be written

$$\begin{pmatrix} T_v \\ T_h \\ T_3 \\ T_4 \end{pmatrix} = \begin{pmatrix} T_v \\ T_h \\ T_{+45^\circ} - T_{-45^\circ} \\ T_{\mathrm{lc}} - T_{\mathrm{rc}} \end{pmatrix} = \frac{\lambda^2}{\eta k_B} \begin{pmatrix} \langle |E_v|^2 \rangle \\ \langle |E_h|^2 \rangle \\ 2\Re e \langle E_v E_h^\star \rangle \\ 2\Im m \langle E_v E_h^\star \rangle \end{pmatrix} \quad (1)$$

where $T_v, T_h, T_{+45^\circ}, T_{-45^\circ}, T_{\mathrm{lc}}, T_{\mathrm{rc}}$ are the vertical, horizontal, orthogonal linearly polarized measurements skewed 45° and -45° with respect to normal and left and right-circularly polarized brightness temperatures expressed in Kelvin. E_v and E_h are the complex vertical and horizontal field amplitudes for a narrow band of frequencies about f. The brackets $\langle \ldots \rangle$ denote a time-average process. η, λ, and k_B are wave impedance, wavelength and Boltzmann's constant, respectively.

In addition to the commonly used first and second Stokes parameters, the third and fourth Stokes parameters also contain useful information about the Earth's environment. The dynamic range of the signal in these parameters, which are effectively the cross correlation of vertical (V) and horizontal (H) polarized field quantities, is typically only a few Kelvin. A primary example is the measurement and retrieval of ocean wind directions as illustrated in [1]–[5] where the amplitude variation with wind direction of the third and fourth Stokes parameters is a maximum of 6 K peak-to-peak. Theory predicts similar directional information in anisotropic scenes like tilled soil [6] and, by inference, row crops. We observed nonzero third and fourth Stokes parameters in the C-band brightness temperatures of a corn canopy during our seventh Radiobrightness Energy Balance Experiment (REBEX-7). As in the case of ocean wind direction retrieval, the dynamic range of the third and fourth Stokes parameters for corn was only a few Kelvin. For these observations to be meaningful, radiometers must be designed both to yield minimum uncertainty in the third and fourth Stokes parameters and permit careful calibration of these parameters. These design and calibration requirements motivated the research reported here. The analytical calibration was used in the analysis of data from REBEX-7, results of which are discussed in Sections V and VI of this paper.

Several approaches have been used to calibrate the third and fourth Stokes parameters. They can be classified into three categories: external polarimetric calibration devices, geophysical model-based calibration, and analytical methods [7]. The first two calibration approaches consider the polarimeter as a single unit and apply an end-to-end calibration. The first category requires a standard external polarimetric target. The approach, e.g., [8] and [9] has the advantage of being able to calibrate nearly any polarimeter as long as a sufficiently large and homogeneous target can be constructed and a sufficiently precise mechanical setup is achieved. The second category requires a geophysical model [10]. This technique is attractive in situations when it is not practical to place a portable calibration target in front of the radiometer. Assuring a robust and reliable model is an obvious limitation of this approach. The end-to-end nature of these calibration techniques offers the advantage of minimum accumulation of errors.

The third category, the analytical calibration method, until now only discussed in radio astronomy [11], requires identification of the radiometer functional blocks, laboratory measurement of the transfer function of each functional block, and creation of an instrument simulator based on the accumulated performance

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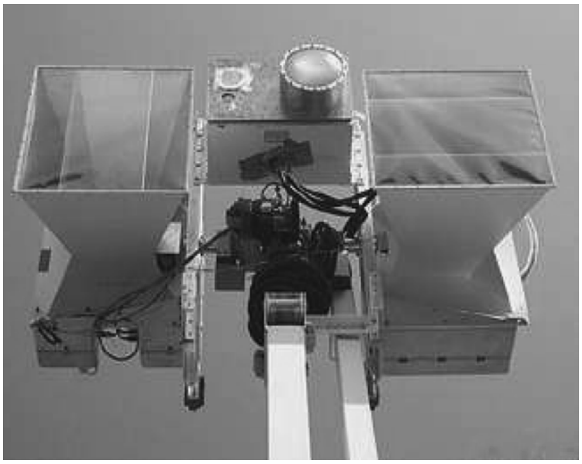

Fig. 1. ACMR mounted on the boom of the truck-mounted radiometer system during REBEX-7. ACMR is in the center. The large square horns on either side are for a separate L-band system not described in this paper.

of the functional blocks. Advantages of this approach are that it avoids assumptions of instrument linearity, and it provides engineering feedback about the contribution to calibration error of each functional block within the instrument. Neither of the first two calibration approaches offers subsystem level feedback. The disadvantage of the analytical approach is the potential for accumulated calibration error that could render the approach less accurate for some applications than an end-to-end approach. Use of a correlated noise calibration standard [12] represents a mixed calibration approach that is flexible enough [13] for semi-end-to-end calibrations (the antenna being excluded) or where noise is injected at each successive stage of the instrument. The latter case is similar to the analytical method.

Analytical methods are particularly well suited to polarimeters whose functional radio-frequency (RF) blocks are easily separated. The National Aeronautics and Space Admnistration (NASA) Goddard Space Flight Center (GSFC) polarimetric airborne C-band microwave radiometer (ACMR), as a polarization combining radiometer, has this architecture and is used to explore the strengths and weaknesses of this calibration method.

The paper is arranged as follows: Section II describes the forward model used to account for ACMR subsystem characteristics, Section III describes the experimental characterization of the system blocks, particularly the antenna measurements for passive polarimetry, Section IV is a discussion of the numerical uncertainties related to Stokes parameter retrieval, and Section V illustrates Stokes parameter retrieval from ACMR observations during REBEX-7. Our findings are listed in Section VI.

II. Forward Model Description

A. Sensor Description

The analytical calibration method targets instruments where distinct, functional RF blocks can be identified.

The GSFC Airborne C-band Microwave Radiometer (ACMR) belongs to this class. It was originally built as a dual-polarized (horizontal and vertical) radiometer centered at 6.8 GHz, with a 200-MHz bandpass; see Fig. 1. A polarization combining network was added to generate the $\pm 45°$ linear and right and left circular polarizations. The sensor can be decomposed into the following four stages:

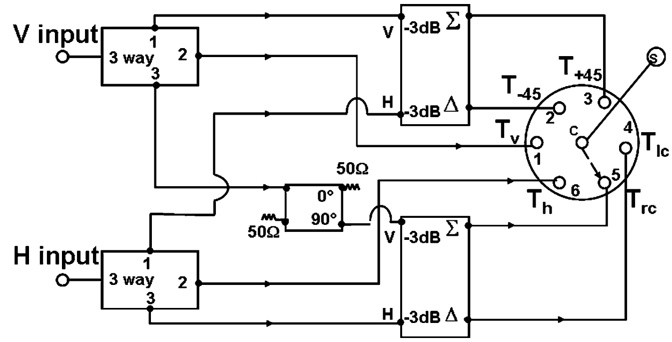

Fig. 2. Polarimetric combining circuit.

- antenna, followed by an orthomode transducer;
- remote receiver module (RRM) including calibration switches, low-noise amplification and filtering;
- polarimetric combining circuit (PCC); see Fig. 2. It features two three-way power dividers, a 90° phase delay circuit, two "magic tees," and a six-position electromechanical switch. Magic tees are broadband hybrid couplers, that are modeled as reciprocal four-port devices providing two equal amplitude in-phase signals when fed from their sum port ($\sum$) and two equal amplitude out-of-phase signals when fed from their difference port ($\triangle$). The sum of two signals input at the ports labeled (-3 dB) will appear at the sum port, and their difference will appear at the difference port. The result is that T_v appears at position 1 of the switch, T_{-45} appears at position 2, etc., as indicated in Fig. 2.
- the last stage with the local receiver module (LRM) and a gain chain ending in a square law detector diode. The LRM output is digitized by an analog/digital converter (ADC) and results are stored in a computer. The ADC subsystem is not examined in this paper.

The link between the detector and the computer is stable and the radiometer is tightly thermally controlled to stabilize the gain of the system [14].

VI. Conclusion

Analytical calibration of passive polarimeters is most readily applied to systems having distinct functional RF blocks. The approach relies on well-controlled laboratory experimental characterization of a radiometer's subsystems. In our calibration of the ACMR, we found that uncertainties in the final calibration were due mainly to the limiting accuracy of available vector network analyzers.

Analytical calibration with currently available laboratory instruments is suitable for applications requiring accuracies of 1–2 K. Where better accuracies are desired, analytical calibration still serves as an instrument simulator enabling assessments of the impact of subsystem improvements on overall system performance, and guiding future instrument design.

Analytical calibration of the ACMR enabled the first polarimetric brightness observations at C-band of senescent corn. As the symmetry of such a row crop suggests, the polarimetric signal for senescent corn depends upon azimuth angle. The amplitude of the azimuth-dependent signals in the third Stokes parameter appears to be 5 K. Clearly, there is information about such vegetated land targets in the third (and possibly the fourth) Stokes parameters that might be exploited. This possibility offers new avenues for research.